When man went into orbit he was literally forced to leave behind one of his oldest and ~~most~~ more useful scientific instruments, the gravimetric mass scale. At the same time there was an urgent requirement for mass measurements in space medicine since weightlessness not only made all existing weighing machines useless, but at the same time produced weight loss and other effects that could be documented only on earth. ~~To properly study such effects [comes the] some method of non-gravimetric mass measurement was required to perform a mass balance study.~~

The balancing of gravimetric force of attraction of an unknown mass against that of a known is such an efficient, simple, and accurate method that no alternative methods were required; and indeed none were available since the development of balances in Egypt before 3000 ~~BC~~ B.C. To study man and many other phenomema in space some alternative to the gravimetric scales were required.

Skylab for the first time will attempt to validate a practical non-gravimetric mass measurement system for both men and specimens. Further, a rather comprehensive mass balance study of the crew will be conducted using two Specimen Mass Measurement Devices of 1 Kgm capacity and a Body Mass Measurement Device of 100 Kgm capacity. Since these devices are such a radical departure from previous gravimetric methods and impose different interface requirements, a somewhat detailed description of the methodology and development will be presented as a necessary introduction to actual experiment description.

It was obvious that some alternative to gravimetric measurement was required. Solution of this problem was a lively challenge to many who proposed various schemes and to a few who tried to reduce theory to practice.

Table 1 lists most of the ~~candidate~~ proposed schemes to date, but cannot begin to cover the possible variations. A science fiction writer[1] was the first to propose non-gravimetric mass measurement. Others that have proposed various schemes include Lockheed A/C,[2,3] Douglas A/C,[4,5] ~~Adam~~ Adams[6] and Thornton[7]. Construction and test of MMD's include Douglas A/C,[5,8] ~~Lock-~~ Lockheed A/C,[2,9,10,11] Thornton[12,13,14] and NASA Ames[15].

In 1965 no MMD was available nor did it seem that work then in hand would yield desired accuracies so the author began an in-house development at Aerospace Medical Division supported by the School of Aerospace Medicine shop. Ultimate goal was a practical MMD which would weigh humans to $\pm$0.25# and smaller versions for food and waste to $\pm$1% accuracy.

The linear spring mass oscillator was chosen on the basis of available space, ease of construction, ability to test under 1-g, and simplicity of associated instrumentation. Given the size and relaxed performance requirements of Skylab this probably would not be the method of choice today.

Basic scheme of this oscillator is shown in Figure 2. A linear extension compression spring is clamped to an infinite mass at one end and to a rigid sample mass at the other. A linear mechanical resistance is in parallel. If the mass is displaced a distance and released it will undergo sinusoidal oscillation[1] whose period in Eg2 is obtained from soln. of Eg1. An electronic counter may be arranged to time the period of one or more cycles, and this in turn allows calculation of mass. The first order of business was demonstration that such a mechanical system could in fact realize accuracies of 0.1% or more with solid masses. To do this an air bearing was used to constrain motion to translation and virtually eliminate friction. A major problem with previous units was large and variable friction forces. Other improvements included an optical crossing detector with resolution of a few micro-inches and a release mechanism which did not ~~an~~ induce significant starting transients and precision springs which did not drift or creep. With such an arrangement it was possible to demonstrate accuracies of $\pm$0.1% using linear calibration curves and $\pm$0.1% using curve fitting. Factors which produce variation in such an oscillating MMD include any vibration of attached or sample mass, any coupled compliance, air currents, and the finite mass of a space ship to which it is attached.

After feasibility demonstration the challenge was coupling non-rigid man with internal force generators into such an oscillating system while maintaining the required accuracy. Figure ________ shows a mechanical analog of the human body in terms of vibration analysis. From experiment and analog simulation it became obvious that the thoraco abdominal viscera and non-rigid coupling of the body to the pan were the chief sources of error. Instead of the simple oscillator shown in Figure 1 a series of oscillators resulted with a complex solution to the equation of motion. This has the effect of lowering the frequency of oscillation, hence producing a ~~posi~~ more positive error. These secondary oscillations cause increasing errors as they approach the natural frequency of oscillation. The only solution is to either damp the oscillations or decrease the compliance; ~~ile~~ i.e. make all elastic couplings stiffer. A second aspect of the body compliances is that they are non-linear, hence displacements by large accelerations must be avoided. This requirement was satisfied by low frequencies and amplitudes of ~~oscillation.~~ oscillation.

From Coermann's[15,16] and similar work it appeared that the human body should behave as a solid mass below oscillation frequencies of 1Hz at low amplitude. For accuracies we were trying to achieve this was not the case as may be seen from Figure 3 showing errors as a function of period of oscillation with the subject lying supine. A ~~kp~~ period of 5 secs. was required to asymptoticly approach zero error. Other factors which had to be considered were a buoyancy correction for gravimetric scales, a factor not present in the non-gravimetric system. Conversely slowly oscillating bodies carry an appreciable volume of air with them[16] and do not simply move through it.

This, however, is a relatively constant for a given atmosphere and small error. Of more importance are the subject's internal force generators:* 1) voluntary motion ~~1~~2) involuntary motion, ~~2~~3) respiration, and ~~3~~4) ballisto cardigram. Fortunately ~~1.~~1) can be well controlled voluntarily while the frequency components of ~~3~~4) are sufficiently for above the frequency of the oscillator to have negligible effects. 2) was not a significant Factor - Respiration produces large errors, hence breath must be held during measurement. This imposes a lower limit on oscillator period, especially in an O_2 rich atmosphere. This limitation forced us to seek ways of making the body more rigid. The approach consisted of placing as many muscles as possible in tension, achieving the greatest areas of attachment to the seat at the highest possible pressures, and reducing slosh of thoraco-abdominal viscera. The ~~optimum~~ present position was reached after a great deal of experimentation ~~but~~ & allowed periods on the order of 2 secs. to be used.

~~The n~~Next step was translation of experimental into flight hardware. Although air bearings could have been used, elimination of a pressurized gas supply was desirable. This was accomplished by use of a ~~meca~~ mechanical structure known as a flexure pivot made of a proprietary spring material such that oscillation was still restrained approximately to translation in one axis with an integral spring function. The solutions of equation of motion are sufficiently close to those for the linear spring mass oscillator to be used. There are other limitations imposed by this arrangement which will not be discussed here. Integral electronics were required,and the schematic of the digital electronic system by Mr. Richard Lorenz is shown in Fig. 4. It was originally planned to use integral batteries, and this was done in the prototype. Prototype SMMD is shown being tested in zero-g ~~air-e~~ aircraft flight in Fog. 5 and the prototype BMMD is shown in Fig. 6. Accuracies of these units are shown in Fig. 7 and 8; however, the BMMD was never flight tested.

Finally flight hardware to meet various requirements for SL were constructed by SWRI based on the prototype design. The SL SMMD experiment consists of two instruments, one in the wardroom and the 2° in the head. Objectives of this experiment (M074) are: 1) Demonstration of accurate nongravimetric mass measurement.

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